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OPERANT BEHAVIOR AND COLONIC TEMPERATURE OF RHESUS MONKEYS,  
Macaca mulatta, EXPOSED TO MICROWAVES AT FREQUENCIES  
ABOVE AND NEAR WHOLE-BODY RESONANCE

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PENSACOLA FLORIDA

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EXPOSED TO MICROWAVES AT FREQUENCIES ABOVE AND NEAR WHOLE-BODY RESONANCE

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## SUMMARY PAGE\*

### THE PROBLEM

Microwave radiation is extensively used in environments occupied by naval personnel. Recently scientific reports have indicated that behavioral changes can be induced by relatively low levels of microwave energy. The reported behavioral changes do not reflect the beneficial or detrimental nature of such changes. The present study was designed to produce in a non-human primate a behavior analogous to human behavior and discover if that behavior was enhanced, disrupted or not affected by microwave energy from radar sources similar to those currently in use in naval communications and weapons systems.

### FINDINGS

Performance by five rhesus monkeys on an observing-response task requiring sustained vigilance was assessed when the monkeys were consecutively exposed to microwaves at frequencies of 1.3 GHz, 5.8 GHz, and 225 MHz. Observing-response performance was impaired at increasingly intense power densities at all frequencies. The threshold power density necessary to disrupt performance at 225 MHz was 8.1 mW/cm<sup>2</sup>; at 1.3 GHz it was 57 mW/cm<sup>2</sup>, and at 5.8 GHz it was 140 mW/cm<sup>2</sup>. These power densities were associated with increases in colonic temperatures above sham exposure levels. The mean increase was typically in the range of 1 °C and response rate changes were not observed in the absence of concomitant temperature increases.

### ACKNOWLEDGMENTS

Mr. Clayton Ezell was responsible for building the restraint device, its holder and the daily routine of conducting these animal experiments. His assistance was invaluable and the completion of this series of studies could not have occurred without him. All of the Bioenvironmental Department Staff provided continuous help but of particular assistance were R. G. Olsen, Toby Griner and Mike Reddix. I also wish to thank Mrs. Anna Johnson, Ms. Eloise Williams and Ms. Cathy Roberts for their assistance in preparation of this manuscript.

\* The animals used in this study were handled in accordance with the principles stated in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council, DHEW, NIH Publication No. 80-23, 1980.

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## INTRODUCTION

Microwave irradiation is frequently encountered by naval personnel engaged in duties associated with communication, detection and weapons systems. Such irradiation has been shown to produce heating in both the peripheral and internal body tissues of animals depending upon animal size and microwave frequency and intensity (12). Behavioral changes associated with body heating are also well-documented (17). In addition, where body heating is less demonstrable, behavioral thermoregulation has been shown to be affected at relatively low power densities (1). Thus naval personnel may be heated by microwaves and their performance may be affected by such heating.

Man has seldom been a subject in microwave investigations in the laboratory, and information is virtually nonexistent. Because of the potential hazards involved, man is not likely to be used as a subject in microwave experiments; consequently animals have typically been used. Most behavioral experiments have used rats thereby limiting the applicability of the findings to the case of humans. Behavioral measurements in these rat experiments have also tended to measure general motor activity as the primary index of a microwave effect. An assessment of the qualitative nature of a microwave effect is difficult to make when general motor activity is measured. For example, an increase in motor activity produced by microwaves fails to indicate either a beneficial or detrimental effect.

Recently, behaviors maintained by schedules of reinforcement have been found to be sensitive to microwave irradiation (17, 18). Scheduled behavior can be arranged to simulate human behavior in specific cases. One such instance is performance of a vigilance task wherein an animal can be trained to produce observing-responses resulting in different stimuli that are to be detected (8). In addition performance on a vigilance task can easily be assessed as to its improvement or disruption by a physical agent.

An animal model much closer to man on the phylogenetic scale than the rat is the rhesus monkey (*Macaca mulatta*). The rhesus monkey is also an excellent model for temperature sensitivity when applying the results to man (9). These characteristics and the fact that the rhesus is easily trained on schedules of reinforcement provide justification for using the rhesus monkey as a model for predicting effects of microwaves on man. In addition recent reports on hyperthermia produced by exposing rhesus monkeys to microwaves (11) and dosimetric measurements of rhesus models (13, 14, 15) provide information that allow construction of a relatively complete picture of the biological effects of microwaves.

The present study uses rhesus monkeys exposed at near-resonant and above-resonant microwave frequencies while performing an observing-response (vigilance task). The frequencies of irradiation were chosen to complement an earlier experiment in which rhesus monkeys performing an observing-response task were exposed to 2.45 GHz (4). The results of the present study in conjunction with the earlier study should allow one to speculate on the behavioral effects of exposure of other animal species to microwaves at a corresponding range of frequencies and intensities.

## PROCEDURE

### SUBJECTS

Five male rhesus monkeys (*Macaca mulatta*), offspring of the Naval Aerospace Medical Research Laboratory rhesus monkey breeding colony, served as subjects. The mean body mass (4.3 to 5.7 kg) of these animals increased over the two year duration of the study. The monkeys were food deprived during the experimental stages of the study and were maintained at approximately 92 percent of their free-feeding body mass. Periodically, the animals were returned to ad libitum feeding so that new 100% body masses could be re-established. The animals normally obtained their daily intake of food while performing in the experiment and were supplemented in their home cage with a diet of Wayne Monkey Chow (Allied Mills, Inc. Chicago, IL). Water was continuously available in the home cages.

### APPARATUS

Three microwave anechoic chambers, one for each frequency, were used. These chambers and their accompanying sources have been previously described in detail (6, 11). The chambers were metal shielded and lined with pyramidal absorber. Inside each chamber were two small audio-speakers, one for white noise, the other for discriminative stimuli, a closed-circuit TV camera, a 25 W incandescent lamp and a Styrofoam chair. The noise level inside each chamber varied, but in general, with all devices active including the white noise, it was 74 dB on the C scale. The chambers were ventilated and the lamp was located directly above the center of the restraint chair. The primary difference between the three chambers was their different sizes. The 225-MHz chamber was the largest and the 5.8-GHz chamber was the smallest.

The 225-MHz continuous wave microwave power was provided by a military Type GRT-3 radio set in conjunction with a cavity type amplifier (MCL Model 10270). A AN/TPS-1G radar set (Hazeltine Corp., Little Neck, NY) provided the 1.3-GHz energy pulsed at 370 pps with a pulse duration of 3  $\mu$ s. A AN/SPS-4 radar set (Raytheon Manufacturing Co., Waltham, MA) provided the 5.8-GHz microwaves, pulsed at 662 pps with a pulse duration of either 0.5 or 2  $\mu$ s. Custom made horns were used with the 225-MHz and 1.3-GHz systems and a standard gain horn, Narda Model 643 (Narda Microwave Corp., Plainview, NY) was used with 5.8-GHz system. In all three chambers the front surface of the upright, seated rhesus monkey was irradiated with a horizontally propagated vertically polarized beam.

Incident power density was measured in the absence of the animal and restraint chair with Narda microline isotropic probes. A model 8323 probe was used for the 1.3- and 5.8-GHz frequencies and model 8623B was used for the 225-MHz frequency. The center of the animal's head was located 240 cm from the horn antenna in the 225-MHz study. This location corresponds to 0.78 times the far-field distance. The animals in the experiments at the other two frequencies were positioned at various distances from their respective antennas with their locations in the far-field at low power densities and closer to the horn antenna at the higher power densities. In the 1.3-GHz experiment the animals were never closer to the horn than

0.57 times the normal far-field distance, and in the 5.8-GHz experiment they were never closer than 0.53 times the far-field distance. The power densities reported in this paper refer to those measured in the region normally occupied by the center of a monkey's head while seated in the restraint chair. The center of the animal's head was aligned with the center of the horn in each chamber.

A restraint chair was constructed of Styrofoam (16) and served throughout the study. The chair was equipped with two operant levers placed directly in front of the right and left hands, and a food receptacle on the top surface. The chair with an opening in the seat was built so as to allow continuous monitoring of the colonic temperature of the seated monkey. The chair was situated on Styrofoam guides in each of the chambers in a uniform manner. Food (750 mg Noyes Precision food pellet, The P. J. Noyes Co., Lancaster, NH) could be delivered from outside the chamber via a plastic tube to a depression on the top surface of the chair where it was obtained by the monkey using his tongue and lips.

A Yellow Springs Instruments' (YSI) tele-thermometer, model 401 (Yellow Springs Instrument Co., Yellow Springs, OH) was used to record local chamber temperature in all three chambers. Animal temperature was recorded during a session with a Vitek model 101 Electrothermic Monitor (Vitek Inc., Boulder, CO) in the 225-MHz study, and with a YSI tele-thermometer, model 46 TUC and probe model 401 in the experiments at the other two frequencies. The probes were inserted approximately 10 cm into the rectum of the monkeys after being restrained in the chair and immediately prior to placement into the chamber. The YSI probes had been found not to be perturbed by the two higher frequency microwaves while in the animals.

#### METHOD

The animals were trained to press the two levers by the method of approximations (3). Details of training and a description of the specific task can be found in de Lorge (4) and de Lorge and Ezell (6). The final performance required a monkey to press the right lever repeatedly (an observing response). Each press produced either a 0.7-s tone at a low pitch (860-1000 Hz) or a longer tone of 1.2-s at a higher pitch (1250-3703 Hz). The loudness of the tones was approximately 60 dB C, but specific frequency and loudness varied with the different chambers. The low pitched tone (the signal that food was not available, S<sup>A</sup>) occurred most frequently whereas the higher tone (the signal indicating that food was available, S<sup>D</sup>) occurred randomly on the average of once every 30 seconds. No tones occurred without a lever press. If the left lever was depressed (a detection response), during the higher-pitched tone the tone would stop and a food pellet was delivered. Left lever responses at other times produced a 5-s period during which right lever presses only produced the low tone. If the left lever was not pressed during the high tone the tone went off after 1.2 seconds and the reinforcement schedule would recycle. Right lever presses during either tone had no consequences. The original reinforcement schedule was a random interval of 1 minute, but as the study progressed the animals' behavior became more efficient resulting in the shorter intervals between reinforcers.

A total of 328 sessions were devoted to the 1.3-GHz study; 133 sessions occurred in the 5.8-GHz study and 53 sessions occurred in the 225-MHz study. Sessions lasted for 60 minutes and the animals were exposed, when scheduled, during the session. Approximately five minutes were required to remove the animal from its transport cage and restrain it in the chair with temperature probe inserted. The same amount of time was required to reverse the process following a session. Approximately two minutes elapsed from the time the animal was placed into the chamber to when the experimental session was started. A PDP-8A computer in an adjoining room was used to control the experiment and record data.

The animals were not exposed until several sessions of stable performance on the observing-response task had occurred. Typically three exposures at each power density were given for each subject. Exceptions to this will be mentioned where appropriate. Power densities ranged from 5 to 11 mW/cm<sup>2</sup> in the 225-MHz exposures, from 20 to 95 mW/cm<sup>2</sup> in the 1.3-GHz exposures and from 10 to 150 mW/cm<sup>2</sup> in the 5.8-GHz exposures. In several instances the power densities indicated in the results (Figures 2-6) consist of means between two separate exposure distances in the 1.3- and 5.8-GHz experiments. For example, the power density of 83 mW/cm<sup>2</sup> referred to in the 1.3-GHz study actually was a mean of several exposures at both 80 and 85 mW/cm<sup>2</sup>. In general, exposures occurred in an ascending order. However all exposure sessions were followed by sham sessions, and following a weekend, if behavior was not at baseline levels stable baselines were reestablished prior to microwave exposure. Additional exposures at most previously used power densities occurred in a descending order near the end of each experiment. The exposure sequence in the 225-MHz study was random except that the initial power density was the lowest to which the animals were exposed. The different power densities in the 1.3- and 5.8-GHz experiments were achieved by moving the animals along the Z axis of the horn antenna and by varying pulse duration in the 5.8-GHz experiment. The 1.3-GHz experiment occurred first followed by the 5.8-GHz experiment and the 225-MHz experiment was last. Approximately 70 days separated each experiment.

## RESULTS

As a matter of convenience the results of these studies will be presented beginning with results of exposure to the lowest microwave frequency and proceeding to the highest. Approximately 100 sessions elapsed before all five animals were consistently responding within a session and between sessions on the observing-response lever. Four of the animals also reduced their incorrect responses on the detection lever to low and stable rates. One animal, subject 10, always made an excessive number of incorrect detection responses throughout the study and at times these rates were greater than the observing-response rate. Nevertheless, this animal's performance was affected by microwaves in the same manner as the behavior of the other animals.

The obvious effect of performance when the animals were exposed at adequate microwave power densities was a reduction in observing-response rate. An example of typical performance is shown in Figure 1. This figure contains cumulative records of pressing on the observing-response



# NO. 13

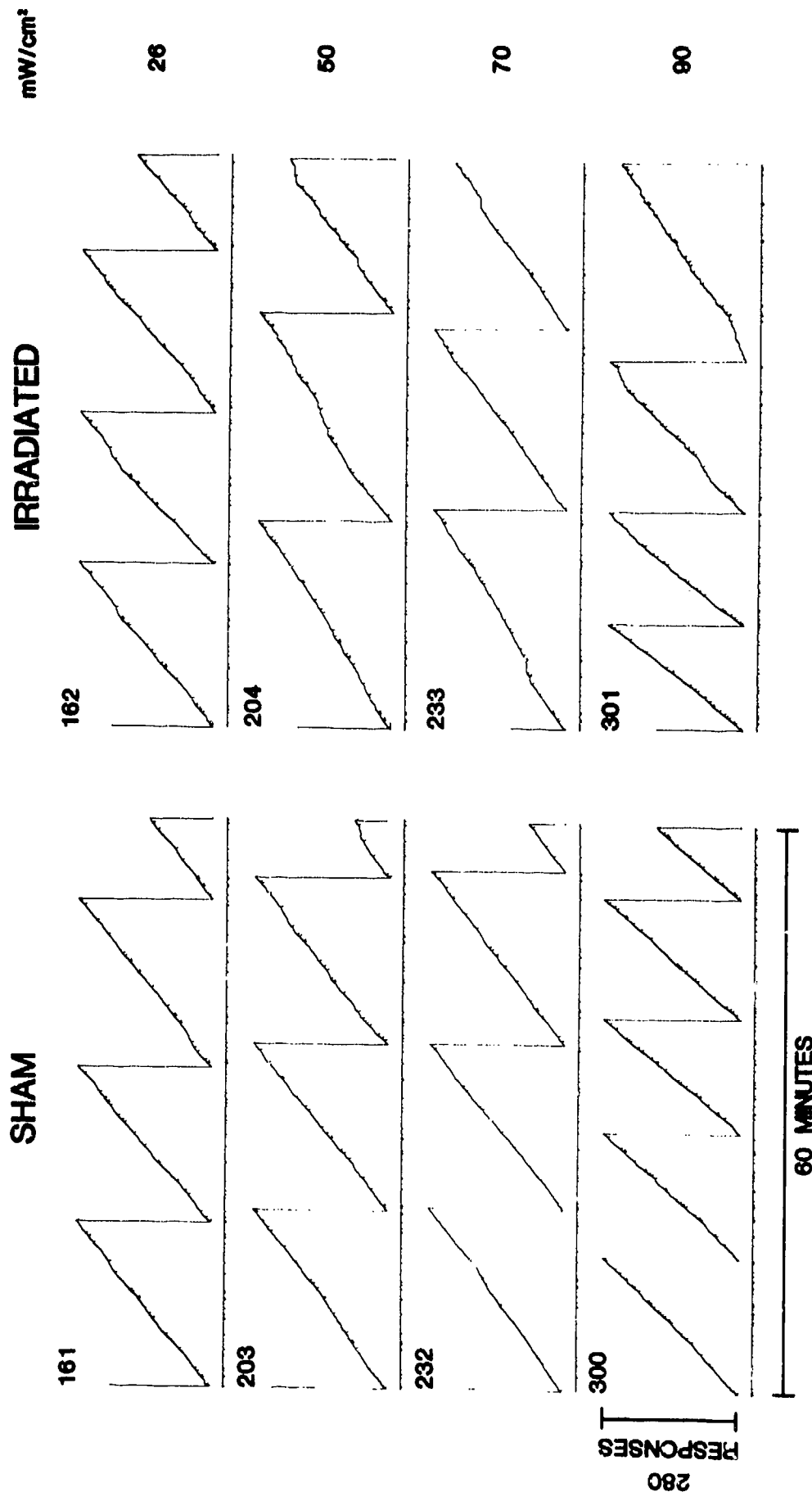


Figure 1. Cumulative records of observing-responses of subject 13 when exposed to 1.3 GHz microwaves. A representative selection of exposures at various power densities as indicated in the right margin is shown. The numbers at the left of each record denote the session number. Sham sessions are on the left and their associated irradiation sessions are on the right.

lever by monkey 13 when exposure to 1.3-GHz microwaves. Selected power densities are indicated on the right and session numbers are shown at the top-left corner of each set of records. Sham sessions occurred on one day followed by irradiated sessions the next day. The response pen stepped upward with each observing response and the response line reset to 280 responses (indicated at lower left) or when the session ended at 60 minutes (indicated by horizontal line at bottom). Hash marks on the response line (slanted lines) denote reinforced detection responses. Deflections on the horizontal lines denote the  $SD$ . As observed in Figure 1 response rates during irradiation sessions were reduced beginning at  $50 \text{ mW/cm}^2$  and this difference became somewhat greater in the latter part of each session as the power density increased. Another aspect of responding while exposed to microwaves was the more erratic pattern on the cumulative record. Animals frequently stopped responding completely. This change in pattern was greatest at 255 MHz when animals paused for as long as 15 minutes and often stopped responding for the last half of a session at  $10 \text{ mW/cm}^2$ . There was less of an effect when the monkeys were exposed to 5.8 GHz. At this latter frequency there was more of a gradual diminution of responding when the monkeys were exposed at the highest power densities and erratic response patterns were less obvious than during the 1.3-GHz exposures.

The averaged performance indices show a more definitive picture than cumulative records alone. Figure 2 illustrates the ratio of observing-responses during irradiation to observing-responses during the previous sham session. Each point represents the mean of means obtained from five monkeys exposed three times at each power density. Exceptions to the number of subjects and exposures, other than that noted in the figure, occurred at the highest power densities where sometimes only four subjects were exposed or some subjects were exposed only twice. The bars illustrate the size of the standard error of the mean. A ratio of 1.0 indicates no differences; 0.9 or 1.1 indicate a 10 percent decrease or increase in responses when comparing irradiated to sham sessions. Power density in  $\text{mW/cm}^2$  is shown on the abscissa and the exposure frequency is shown in the upper-left corner of each graph. At 225 MHz there was a graded effect as the power density increased although the decrease was not significantly different until a power density of  $7.5 \text{ mW/cm}^2$  was used. A large decrease in responding was evident at  $10 \text{ mW/cm}^2$ . The triangle in this graph represents the data of one subject, animal 21, exposed to  $11 \text{ mW/cm}^2$  whose behavior was only minimally affected at lower power densities.

When the monkeys were exposed to 1.3 GHz the graded effect was not observed. At  $50 \text{ mW/cm}^2$  no effect on observing-response rate was evident in the averaged data in contrast to the data of one monkey (Figure 1), whereas at  $63 \text{ mW/cm}^2$  the effect appeared in full-force and became only slightly more pronounced as the power density increased up to  $93 \text{ mW/cm}^2$ .

At 5.8 GHz the effect of microwave exposure on observing-response rate was more variable with rate increases at some power densities. Such increases were not large and invariably depended on the responses of one animal. The only substantial decreases in response rate were first seen at  $140 \text{ mW/cm}^2$  and were magnified at  $150 \text{ mW/cm}^2$ . By observing the power density scales in Figure 2 one can see that as the microwave frequency increased greater power densities were needed to decrease observing-responses.

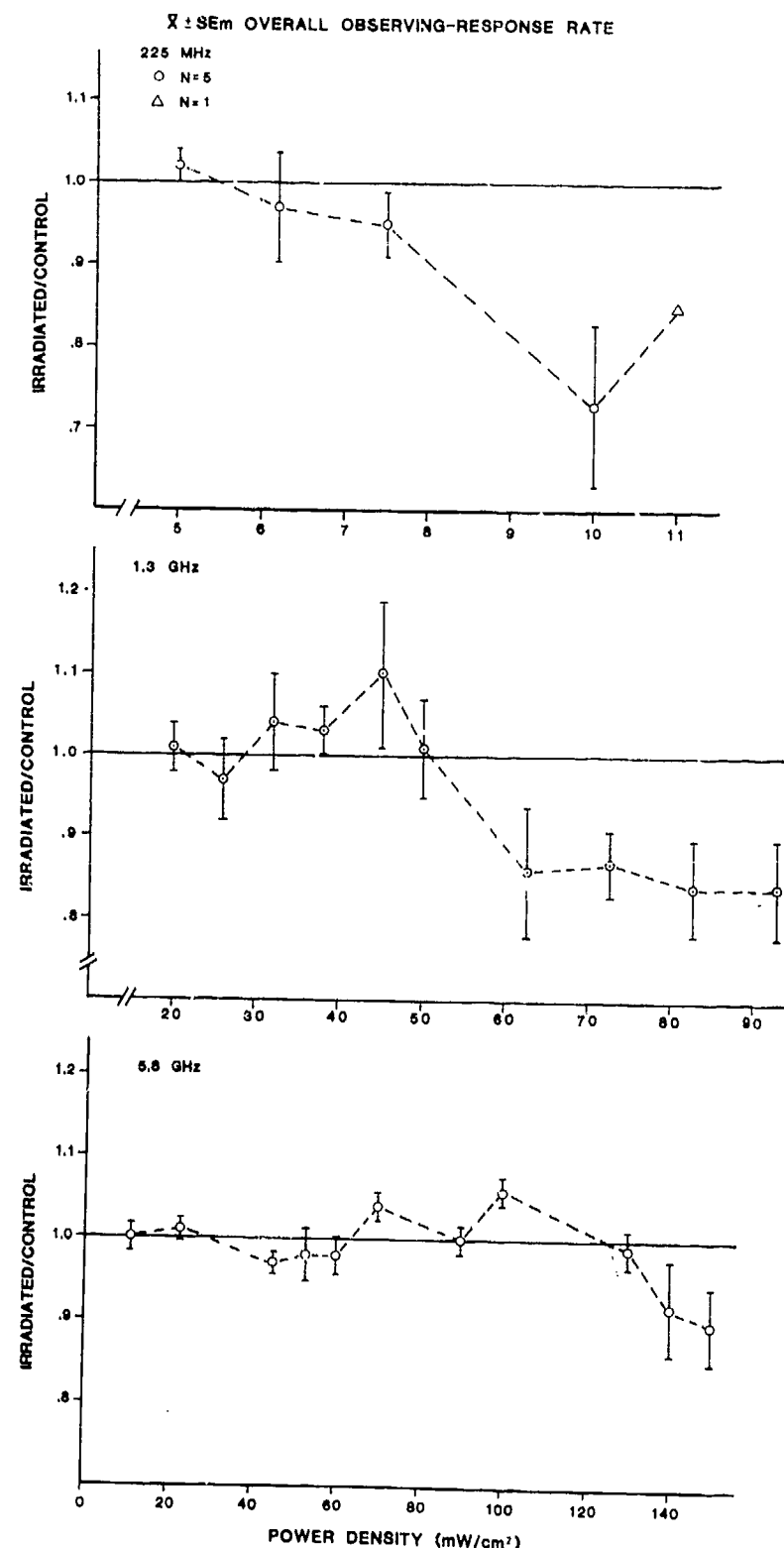


Figure 2

Mean ratios of observing-responses during irradiation sessions to observing-responses during sham sessions. The horizontal lines at 1.0 indicate no differences between the two conditions. Exposure frequencies are shown in the upper-left corner and power densities are indicated on the abscissa of each graph. Vertical bars indicate the standard error of the mean.

The highest power density necessary to produce a decrement in rate at 5.8 GHz, 150 mW/cm<sup>2</sup>, also produced minor facial burns in three of the five monkeys. The worst of these burns occurred between the eyes and orbito-nasal area. The erythema generally disappeared within a few days except in one animal who continued to irritate the area by removing scabious material from the burned area. Similar facial burns did not occur at any other frequencies to which these animals were exposed.

The detection responses on the food lever, as seen in Figure 3, were not consistently affected by microwaves at the three frequencies. No effect was observed at 225 MHz or 5.8 GHz and only at power densities of 83 mW/cm<sup>2</sup> or greater was an effect observed at 1.3 GHz.

There was an interesting finding regarding detection responses that is illustrated by the irradiated-sham ratios of detection-response latencies in Figure 4. At all three frequencies at most power densities the monkeys tended to take longer to make a detection-response during irradiation sessions than during sham sessions. This difference increased with increases in power density at all frequencies although not in a linear fashion, and the correlation coefficients were significant at the .05 level in the cases of 225 MHz and 1.3 GHz ( $r=.81$ , d.f.=3;  $r=.51$ , d.f.=10) but not in the case of 5.8 GHz ( $r=.41$ , d.f.=9). Note also the decrease in variance as the animals progressed from their initial exposures at 1.3 GHz to 5.8 GHz and finally to 225 MHz.

Another effect of the microwaves was found in the post-reinforcement pause (pause after a reinforced detection-response). When converted into ratios of mean pauses during irradiated sessions to mean pauses during sham sessions a graded effect was observed at the 225-MHz exposures shown in Figure 5. The animals paused longer during irradiated sessions and the pauses increased with the power density. Although a similar effect was observed at 1.3 GHz the pauses did not reliably increase until power densities were 63 mW/cm<sup>2</sup> or greater and the increase did not vary directly with increases in power density. The effect at 5.8 GHz was variable and the only large difference in pause times was seen at 150 mW/cm<sup>2</sup>. Even at that power density the pause time was not as substantially affected by microwave exposure as had occurred at the other frequencies.

Associated with the various performance changes were changes in colonic temperature as a function of microwave exposure. Figure 6 illustrates the average increases in colonic temperature as a function of power density when the animals were exposed to the three different microwave frequencies. The ordinates of each of the three graphs indicate the mean temperature difference between increases that normally occurred during a 60-min sham session and those that occurred during the respective exposure session. The bars show the standard error of these mean differences and the dotted lines are the linear regression lines. The mean animal temperature at the start of exposure was 38.6 °C and an average increase of .15 °C generally occurred during the 60-min sham session. At the two higher frequencies the variability of these temperatures might have been caused by the increasing nonuniformity in the field distribution (smaller beam size) as the animals were moved closer to the horn to achieve high power densities.

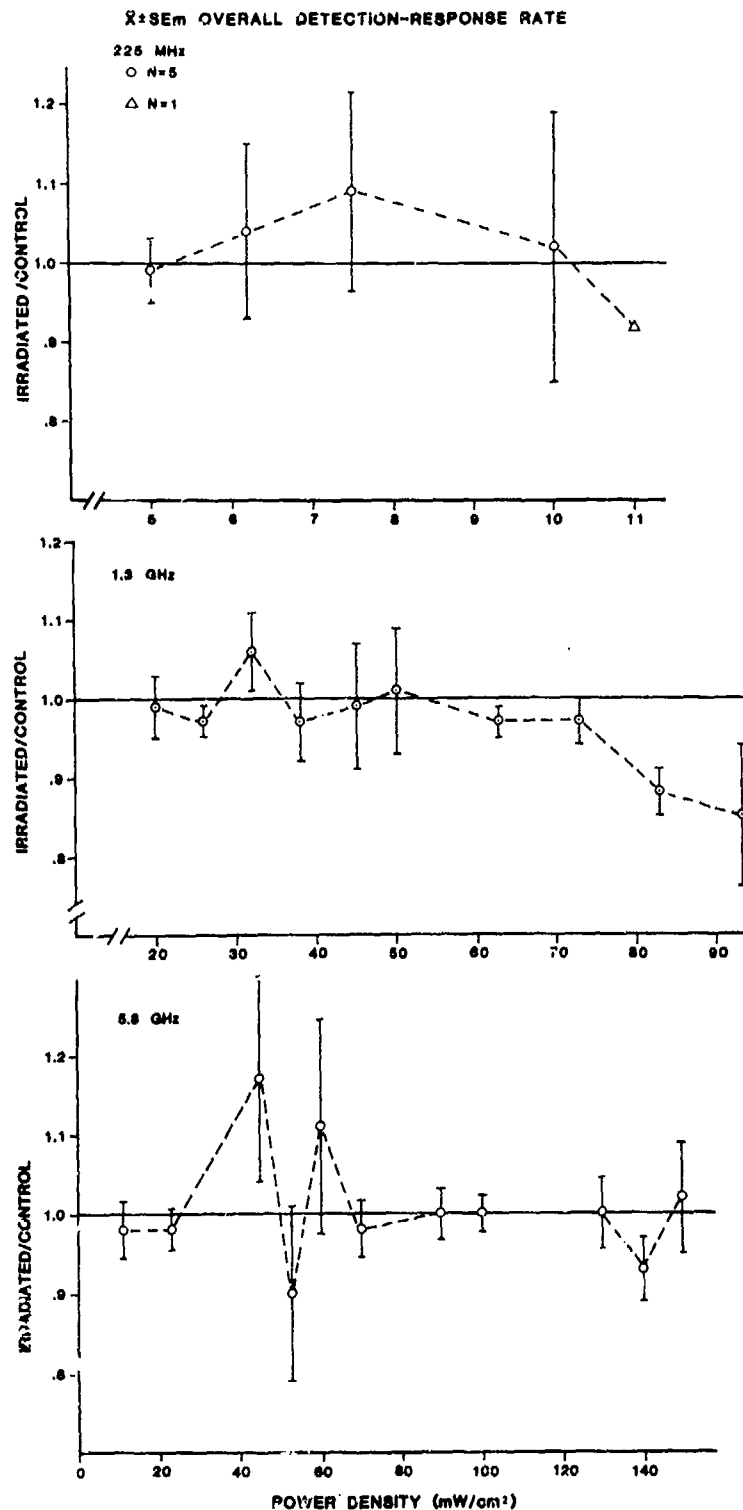


Figure 3

Mean ratios of rates of detection-responses during irradiation versus sham sessions. Indices are the same as in Figure 2.

$\bar{X} \pm \text{SEm}$  DETECTION-RESPONSE LATENCY

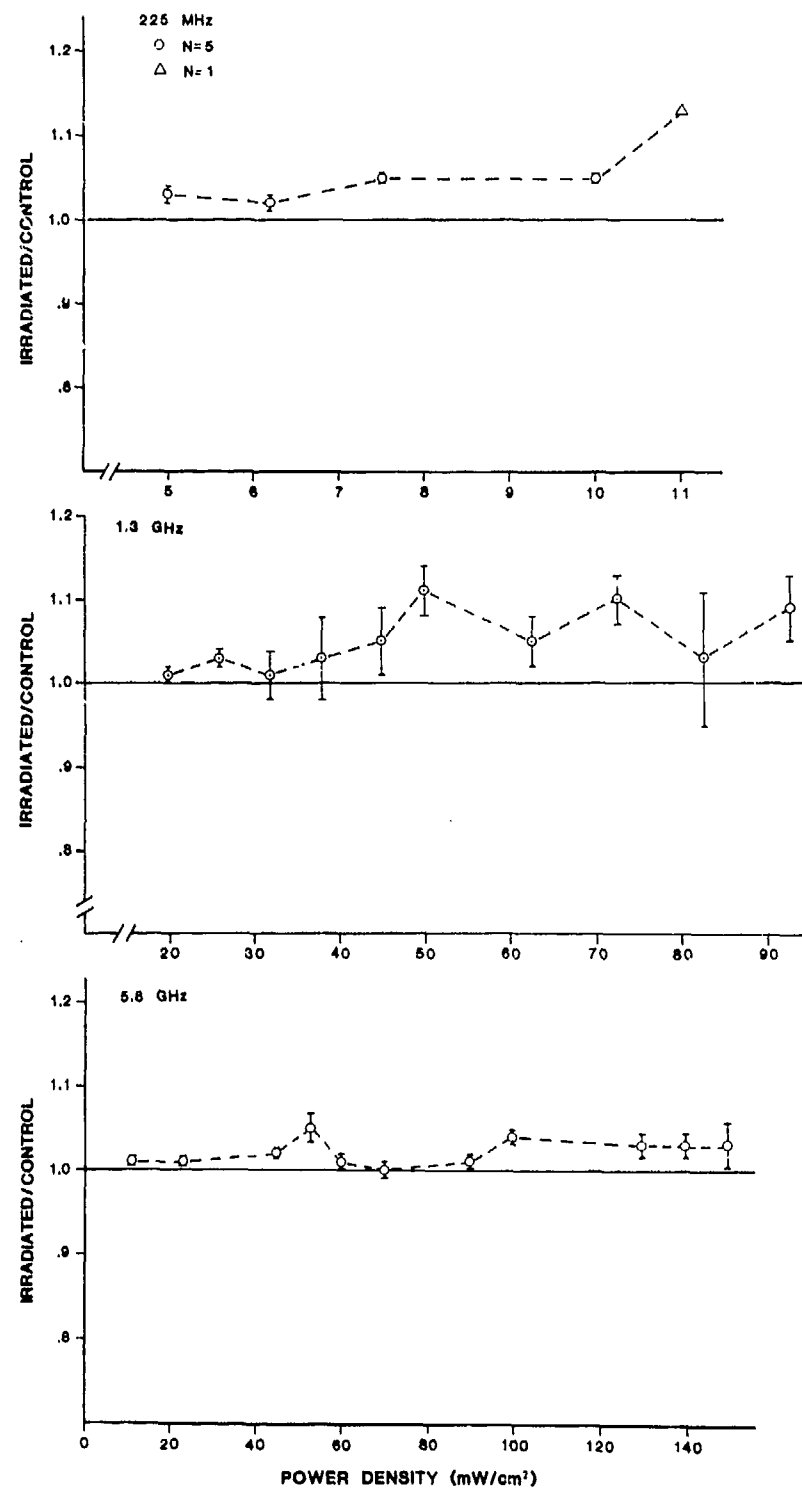


Figure 4. Mean ratios of detection-response latency during irradiation versus sham sessions. Indices are the same as in Figure 2.

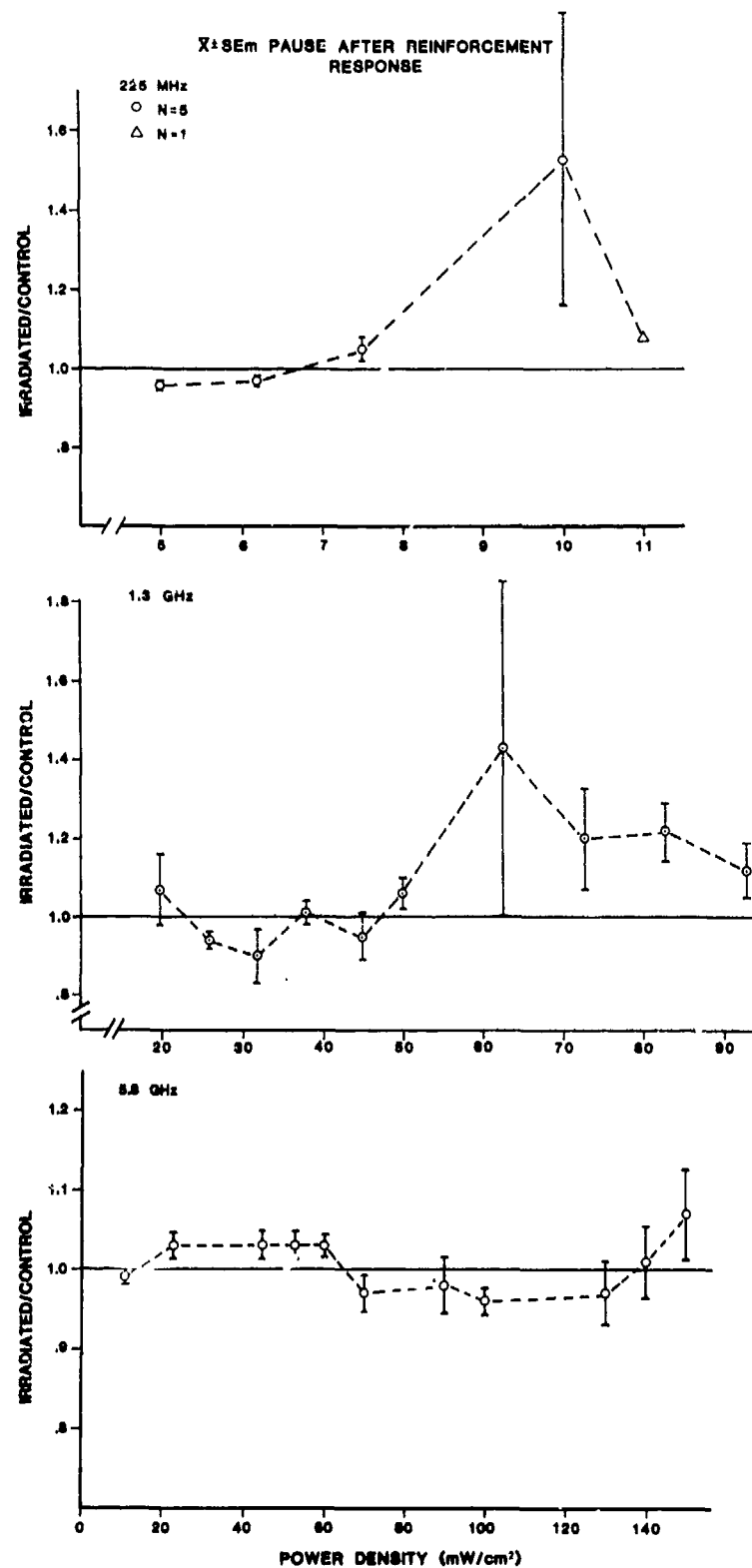


Figure 5. Mean ratios of post-reinforcement pauses during irradiation versus sham sessions. Indices are the same as in Figure 2.

# $\bar{X} \pm \text{SEM}$ COLONIC TEMPERATURE CHANGE

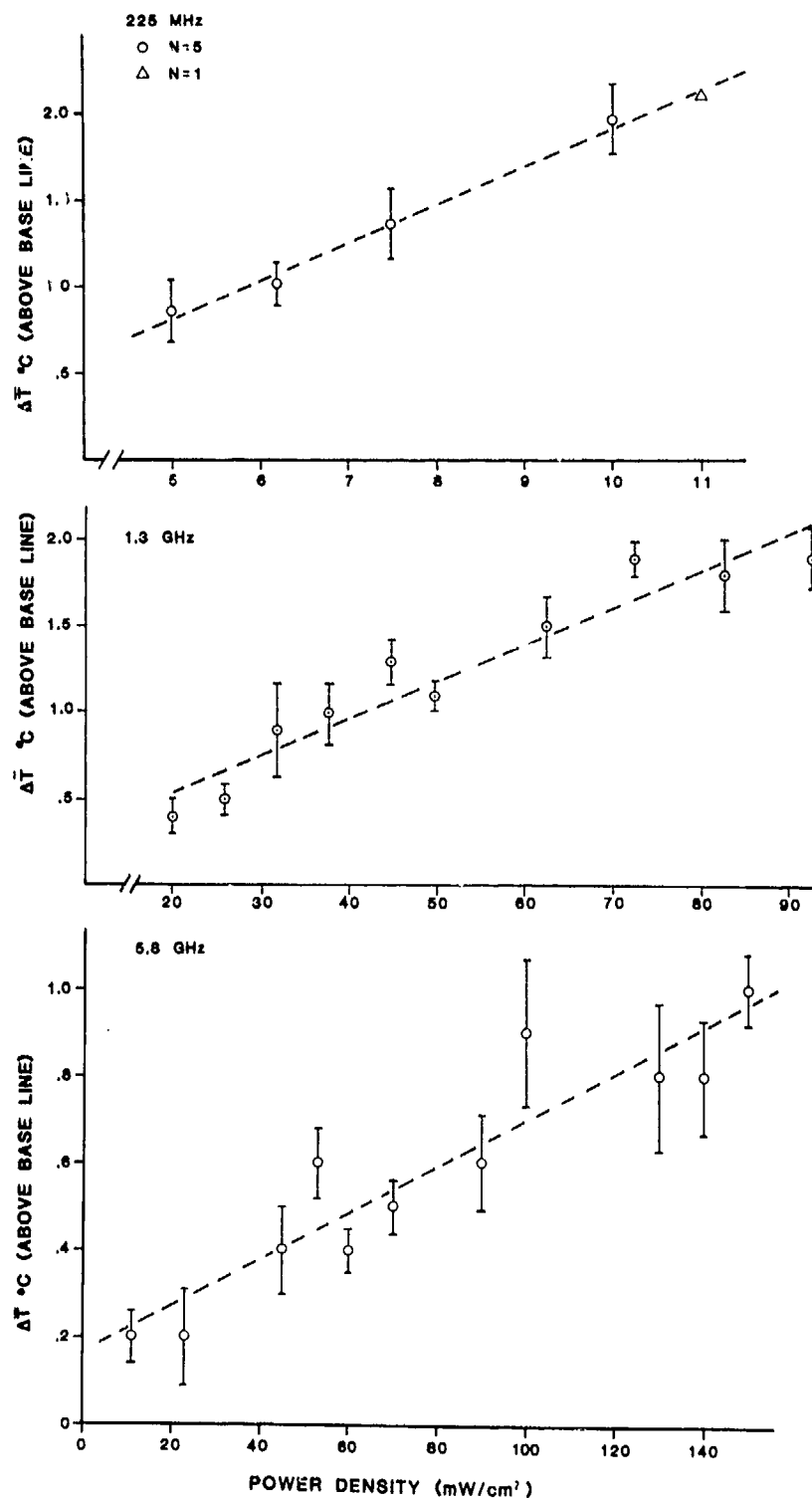


Figure 6. The mean colonic temperature increase (ordinates) as a function of power density (abscissae) when the five monkeys were exposed for 60 minutes to microwave frequencies as indicated in the upper-left corner of each graph. The dashed lines denote linear regression lines.



The temperature data can be best appreciated when seen in a figure based on the same scales. Figure 7 contains the data of Figure 6 in addition to previous results of exposure at 2.45 GHz (4). The lines in Figure 7 correspond to the lines of best fit as denoted by the various formulas shown in the figure. The data points are the same as those in Figure 6 but the standard error bars are not shown. The microwave exposure frequency is indicated by arrows pointing to the appropriate curve. The curve formula is shown in brackets beneath the frequency designation. The exponential curves at 225 MHz and 2.45 GHz are distinctly different from the curves at 1.3 and 5.8 GHz. Note that the highest temperature increases are obtained with the former frequencies. Temperature curves for squirrel monkeys exposed at 2.45 GHz similar to those shown here for the rhesus monkey have been previously reported (5).

#### $\bar{X}$ COLONIC TEMPERATURE CHANGE

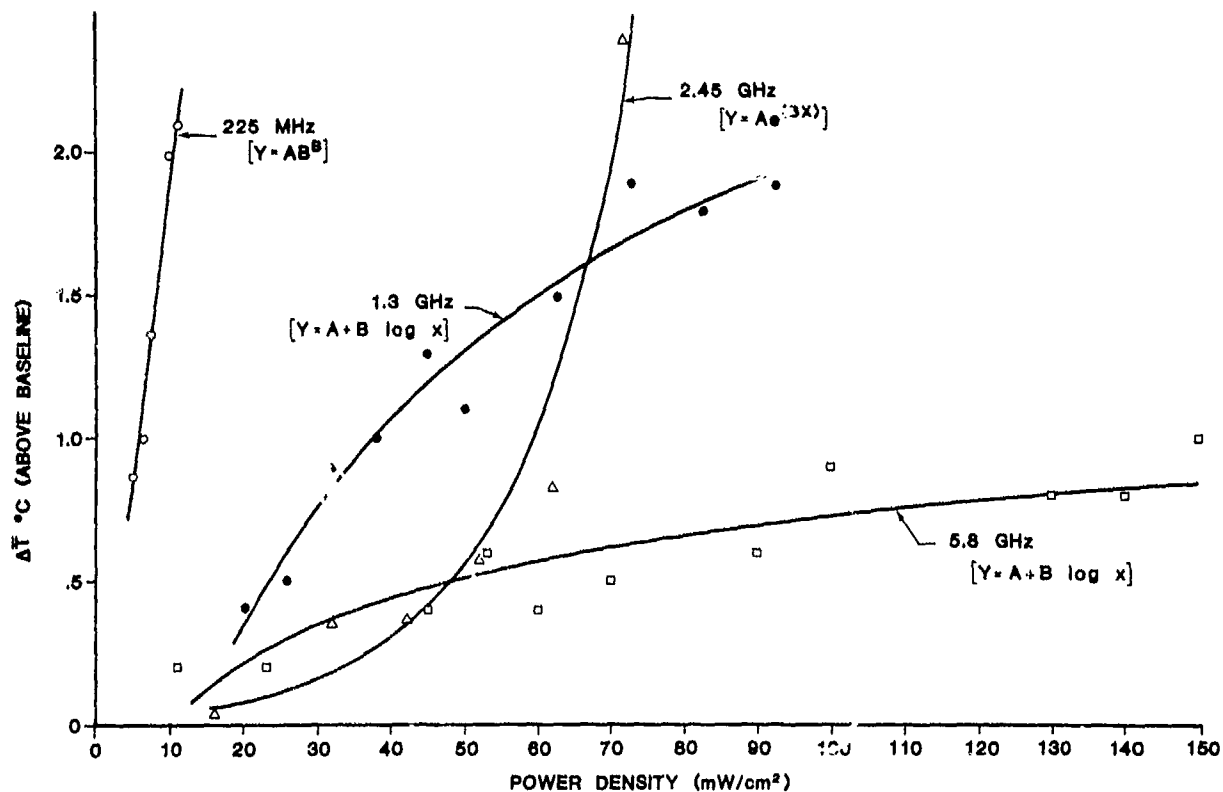


Figure 7

The data of Figure 6 converted to a single graph. Mean colonic temperature increase above sham comparisons is shown on the ordinate and power density is shown on the abscissa. Microwave frequency is indicated with an arrow pointing to its respective curve. The line of best fit formula is in brackets beneath the frequency designation.

Estimates of the absolute threshold in terms of power density for disruption of observing-response rates were made by averaging the power density where no difference in rates occurred between irradiated and sham sessions and where an obvious difference between the two conditions did occur (see Figure 2). An irradiated session was judged not different from a sham session if the standard error bars overlapped the equal ratio line. The highest power density where this occurred was used as the "no difference" estimate. The judgment of an obvious difference between sham and irradiated sessions was made by selecting the power density where a 10 percent or greater difference occurred between the two conditions and the corresponding error bars did not overlap either the equal ratio line or the error bars of the "no difference" estimate. These absolute thresholds were 8.1 mW/cm<sup>2</sup> at 225 MHz, 57 mW/cm<sup>2</sup> at 1.3 GHz, and 140 mW/cm<sup>2</sup> at 5.8 GHz. A threshold of 67 mW/cm<sup>2</sup> at 2.45 GHz was obtained from an earlier experiment (4).

The minimal power densities producing 1 °C increments in colonic temperatures were also calculated at each microwave frequency. These observations (represented by triangles) along with the behavior disruption thresholds previously obtained (represented by circles) are illustrated in Figure 8. This figure contains information from a previous experiment in

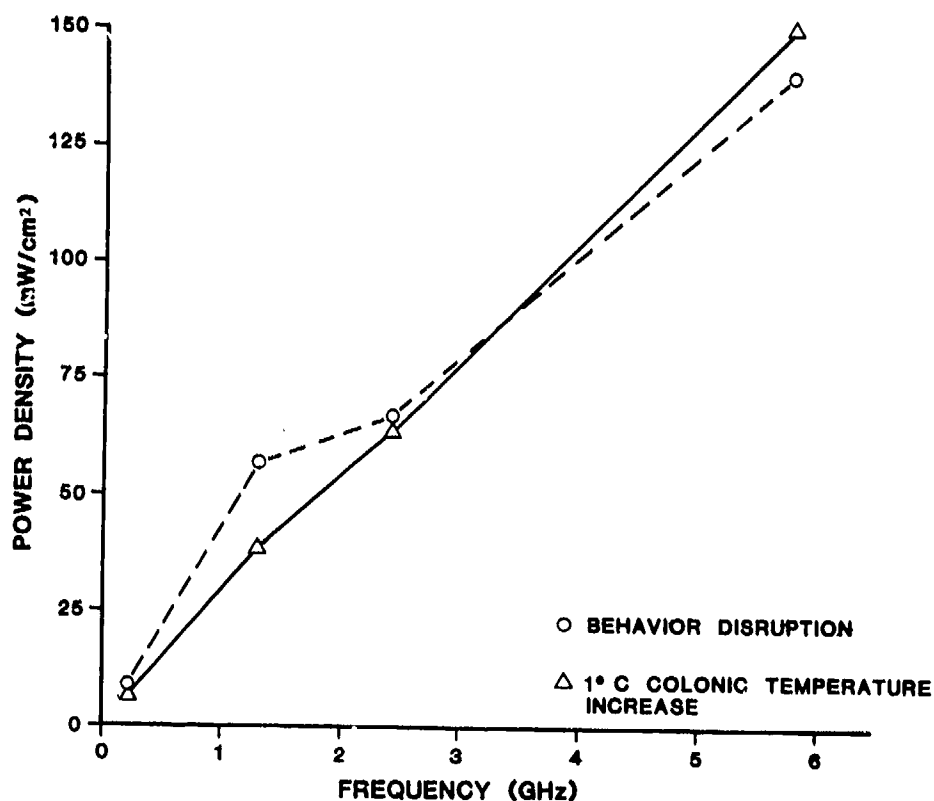


Figure 8. The absolute thresholds of power density for behavioral disruption (circles) and the minimal power densities needed for producing 1 °C body temperature increments (triangles) are shown as a function of microwave frequency (abscissa). Power density is indicated on the ordinate. The 2.46 GHz exposure data are from an earlier experiment (4).

which 2.45 GHz exposures were used (4) in addition to data from the present experiments. These data illustrate that an almost linear relationship exists between power density and frequency when using a 1 °C colonic temperature rise as a measure of a biological effect of microwaves.

The data points for temperature in Figure 8 were transformed into normalized specific absorption rates (SAR) by dividing estimates of SAR by the corresponding power density.\* The results are shown in Figure 9.

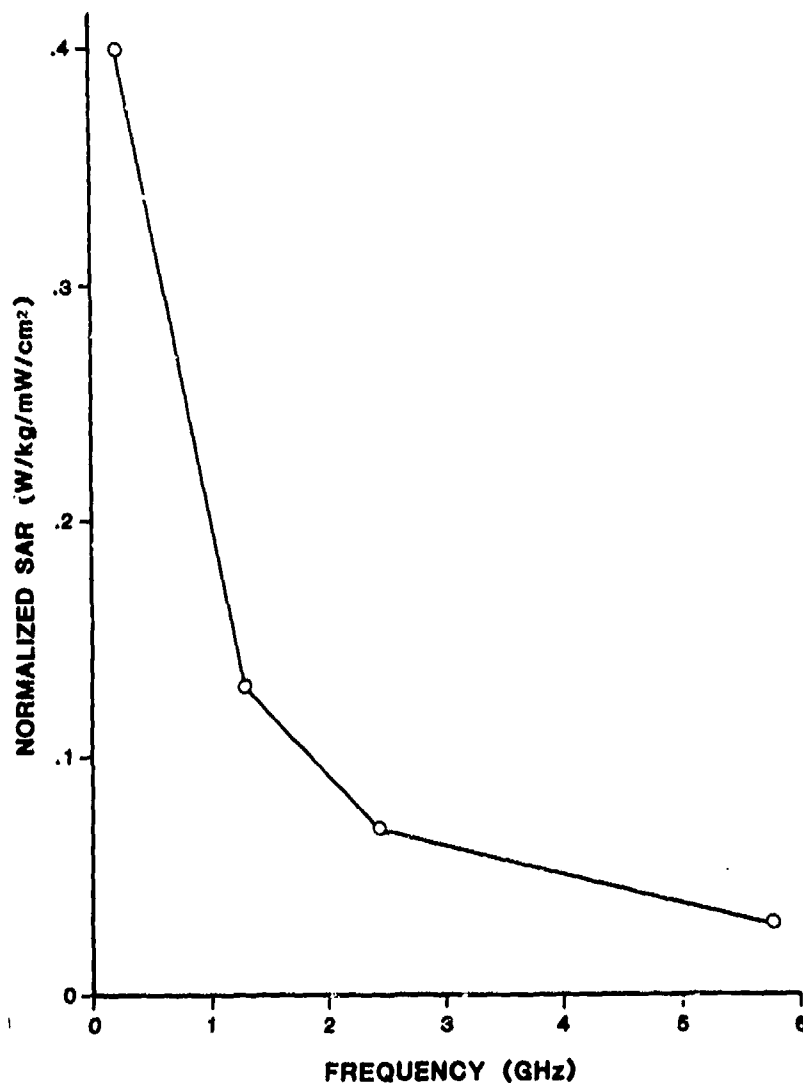


Figure 9. Normalized specific absorption rates (SAR) of energy absorbed as a function of microwave frequency. The SAR is expressed in terms of (W/kg)/mW/cm<sup>2</sup> as shown on the ordinate. This graph illustrates that a monkey exposed to 10 mW/cm<sup>2</sup> at 225 MHz would have a SAR of 4 W/kg.

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 \*The SAR at 5.8 GHz was obtained on flesh-simulating material by this investigator while that at 225 MHz and 1.3 GHz was obtained on saline models by G. Lotz (see reference 11 for portions of this information). The SAR estimate at 2.45 GHz was derived from formulas in Durney, et al (7).

Obviously more energy per milliwatt of power density was absorbed at 225 MHz than at the other frequencies and the rate of energy absorption was a decreasing function of frequency. Although more energy per milliwatt of power was absorbed at 225 MHz, substantially less total energy absorption was required to raise colonic temperature 1 °C (2.5 W/kg). In fact, approximately twice the energy absorption was required to raise temperatures 1 °C at the other three frequencies (4-5 W/kg). Power density requirements, on the other hand, were as much as 6, 10, and 24 times as great at 1.3, 2.45 and 5.8 GHz, respectively, than needed at 225 MHz to raise colonic temperature 1 °C.

## DISCUSSION AND CONCLUSIONS

Several consistent relationships have emerged from the foregoing experiments. Disruption of operant behavior, particularly a highly motivated performance, by microwave irradiation seems to be directly related to increases in core temperature. The relationship is no doubt dependent upon various factors but invariably behavior was not greatly disrupted until body temperature increases were 1 °C unless an animal was actually suffering superficial burns or at least bothered by facial-skin irritation.

The linear relationship between temperature increases and power density as a function of microwave frequency shown in Figure 8 would probably not exist for virtually any other range of frequencies for these animals. However, these results demonstrate that predictions of biological effects based upon power density levels are futile. The SAR information shown in Figure 9 also illustrates the futility of similar predications based on normalized whole-body energy absorption. The only remaining reliable index of a behavioral effect is the 1 °C temperature increase. Other investigations with other animals and exposure durations might reach different conclusions although research in our laboratory substantiates the present findings.

The different amounts of heating as illustrated by the power density and temperature curves indicate that various microwave frequencies probably produce body temperature increases in various, idiosyncratic ways. My speculations regarding these findings are that the 225-MHz data reflect a resonance heating effect where an animal has extreme difficulty thermoregulating because blood is heated throughout the body and there is no way to replace heated blood with cooler blood. The 2.45-GHz data may reflect potential hot-spot heating in the center of the rhesus head. According to Kritikos and Schwan (10) the animals we are using (whose brain radius is greater than the 2.45-GHz wavelength in the brain; 3.5:2 cm) should have a hot spot situated somewhat behind the center of the brain, although others have found localized heating exactly in the center of a rhesus cadaver head (2) and in the center of a rhesus monkey model head (13) at 1.29 GHz. Weil (19) reports the peak internal heating potential of a multilayered 3.3 cm radius sphere is greatest at 2.45 GHz than at the other three frequencies referred to in this study. Weil's research also documents the existence of a hot spot in front of the center of a sphere similar in size to the rhesus monkey brain. These hot spots have ratios of inner versus surface heating of approximately 4 to 1. If these hot spots do

exist in the rhesus monkey head at 2.45 GHz the temperature curve shown in Figure 7 might have been produced by a failure in the animal's thermoregulating mechanism at the highest power density and a facilitation of such mechanisms at the lower power densities. The curves at the 1.3- and 5.8-GHz frequencies may illustrate normal thermoregulation in the monkeys, and limbs or skin are not only differentially heated, but heated to a much greater extent than the interior of the head (2, 13). In neither of the latter two frequencies were the animals ever exposed to power densities that produced increases greater than 2 °C. However, at both 225 and 2450 MHz the animals did reach such large increases.

These results when applied to animals of the other species and sizes, for example, man, will allow one to predict the general effect on behavior while being irradiated at near resonant and above resonant frequencies. No doubt additional research is necessary to validate such a claim, but using body temperature rise as the general indication of the level of microwave energy absorption, predictive curves similar to those generated in the present study could be constructed.

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Performance by five rhesus monkeys on an observing-response task requiring sustained vigilance was assessed when the monkeys were consecutively exposed to microwaves at frequencies of 1.3 GHz, 5.8 GHz, and 225 MHz. Observing-response performance was impaired at increasingly intense power densities at all frequencies. The threshold power density necessary to disrupt performance at 225 MHz was 8.1 mW/cm<sup>2</sup>; at 1.3 GHz it was 57 mW/cm<sup>2</sup>, and at 5.8 GHz it was 140 mW/cm<sup>2</sup>. These power densities were associated with increases in colonic temperatures above sham exposure levels. The mean increase was typically in the range of 1 °C and response rate changes were not observed in the absence of concomitant temperature increases.

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